# CONTINUED BENCHMARKING OF AN FCG CODE

E.R. Parkinson, K.A. Jamison, Science Applications Int'l Corp., PO Box 4216
Ft. Walton Beach, FL 32549
J.B. Cornette, M.A. Cash, Air Force Research Lab., 101 West Eglin Boulevard
Eglin AFB, FL 32542-6810
C.M. Fowler, J.D. Goettee, Los Alamos National Lab
DX3: Hydrodynamic Applications, Los Alamos, NM 87545

*Abstract*

SAIC and AFRL are continuing development of an explosive flux compression generator (EFCG, or FCG) simulation code called, "FCGSCA." FCGSCA is written in FORTRAN and Visual Basic® and targets the Windows95® platform. Its structure and approach has benefitted substantially from both the historic expertise and benchmarking data supplied from LANL. The code uses basic physics principles and well-known circuit analysis techniques to simulate overall FCG-system performance; in particular, it incorporates an armature/stator inductance model, a "flux-loss" model, and a fairly detailed treatment of the stator winding resistance. FCGSCA includes a capability for modeling transformer coupling and fuze switching as part of various load configurations; additionally, the user can view overlays of time-history plots from one or two-parameter variation studies. With reasonable costs in simulation fidelity, this level of detail permits quick system-level simulations that are useful for FCG design and development. Herein, we report on some benchmarking of FCGSCA against the "Ranchito" generator that has been designed and tested by LANL. Our preliminary success with FCGSCA has prompted us to continue to solicit and explore possibilities for other cooperative work in this area.

## I. INTRODUCTION

Researchers have studied and tested numerous types and geometries of FCGs. Due to their inherent high-energy gain, simple construction and modest cost, helically-wound FCGs have proven useful in a great variety of applications [1]. This market, accompanied by the ease of first-order FCG-system modeling, motivated development of a simple, broad-use software package to simulate the operation of helical FCGs while varying generator, connection, switching, load and other important system-level design parameters.

FCGSCA was developed to provide the user with a general FCG design and diagnostic tool from an electrical perspective [2]. Code diagnostics permit inspection of generator voltages and currents and address series/parallel fuze and closing switch timing and operation. Since the overall performance of an FCG depends upon its electrical load, transformer-matching options are also included.

## II. FCGSCA GUI

FCGSCA consists of a Microsoft Visual Basic® graphical user interface (GUI) that drives a dynamic-link-library (DLL) written in FORTRAN. The GUI permits user-friendly and flexible control of the FCG and load configuration. The user edits the load/configuration data file, and runs simulations through the GUI. Major editing options consist of the *mode/configuration* of the FCG (Fig. 1), the *scanned parameters* for families of simulation curves (Fig. 2), the electrical *stray parameters* of the setup (Fig. 3), or the *auxiliary parameters* of the generator (Fig. 4). After the user is satisfied with the simulation setup, the simulation is launched. Simulation times on a modern PC vary from a few seconds to a few minutes, depending primarily upon the number of data points (in time and over scanned parameters) and the circuit topology. Simulation data may be plotted directly in FCGSCA for a "quick-look," or redirected to a tabular text file for importing into other graphics packages.

## III. FCG-LOAD MODEL

A simulation DLL lies at the core of FCGSCA. This DLL incorporates an electrical circuit model (Fig. 5), a quasi-two-dimensional stator-armature inductance calculation, and ancillary calculations including flux loss, stator-armature resistance, fuze resistance, and electrical switching. Like most circuit simulations, FCGSCA simply integrates a set of ordinary differential equations to advance the simulation state variables' time histories.

Modeling the time-varying FCG internal inductance is a critical calculation in FCGSCA. Sufficiently accurate approximations to the inductance functions [3] were used in FCGSCA for convenience. The model segments the armature and stator into coupled, short-solenoid rings. Each armature ring begins to expand toward the stator at a time determined by the axial sweep velocity of the high explosive's detonation front; the ring's radial velocity is determined either by a Gurney estimate or by direct input(s). Successive armature rings have the same radial velocity history, displaced only in time; magnetic pressure—which tends to retard the armature's radial velocity—is ignored.

The total FCG inductance is subdivided into $L_{gen}$ and $L_{loss}$, the latter accounting for generator flux losses. $L_{gen}$ is calculated using standard approximations for the

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# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| 1. REPORT DATE | 2. REPORT TYPE | 3. DATES COVERED |
|---|---|---|
| **JUN 1999** | **N/A** | - |

| 4. TITLE AND SUBTITLE | |
|---|---|
| **Continued Benchmarking Of An Fcg Code** | 5a. CONTRACT NUMBER |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Science Applications Intl Corp., PO Box 4216 Ft. Walton Beach, FL 32549** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR’S ACRONYM(S) |
| | 11. SPONSOR/MONITOR’S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release, distribution unlimited**

13. SUPPLEMENTARY NOTES
**See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.**

14. ABSTRACT
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15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
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| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | |
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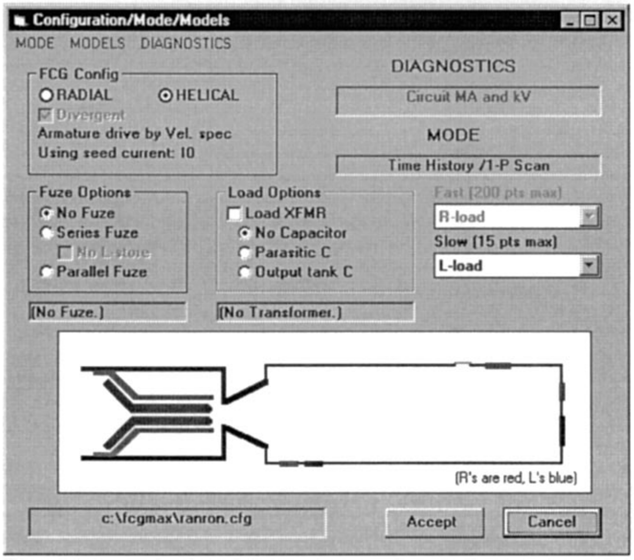


Figure 1. FCGSCA GUI for "mode/model" editing. Note the capabilities for two different FCG configurations, fuze and transformer options, and time histories with one or two parameter variation studies.

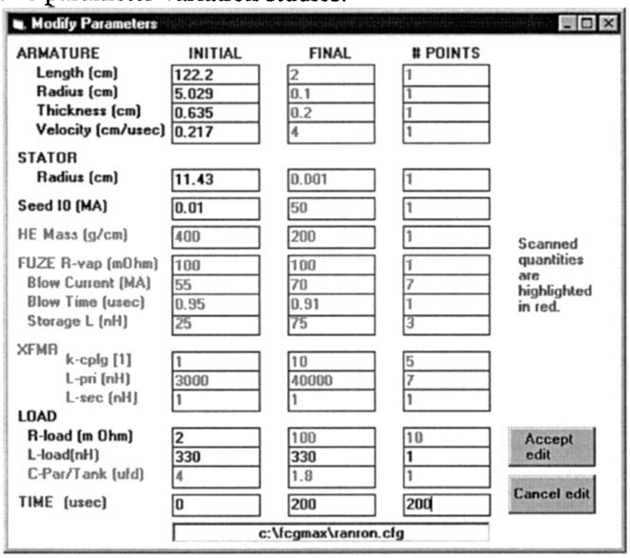


Figure 2. FCGSCA GUI for modifying "scanned parameters." Items "grayed out" are not applicable.

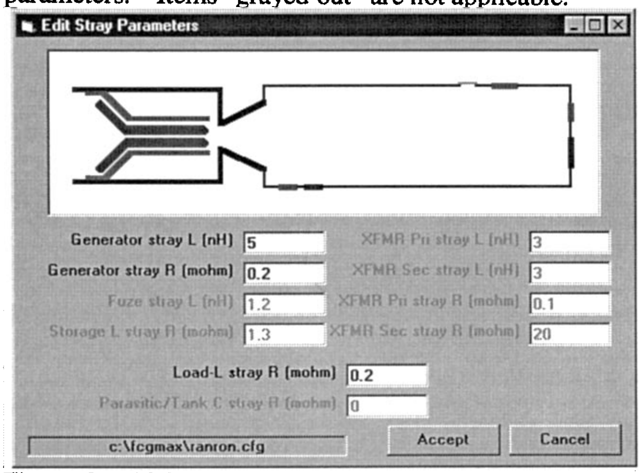


Figure 3. FCGSCA GUI for editing "stray parameters." Items "grayed out" are not applicable.

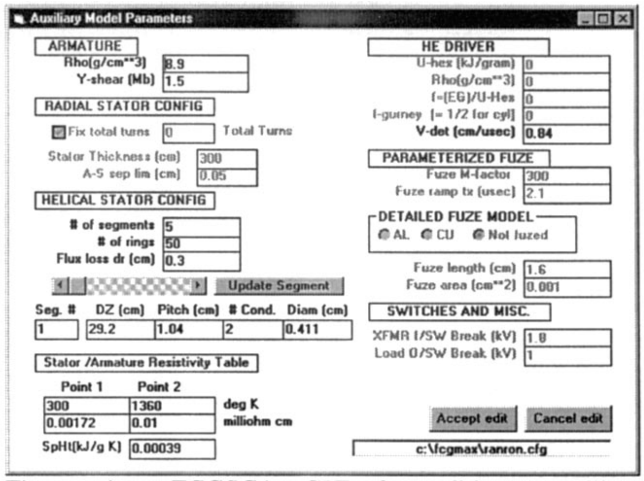


Figure 4. FCGSCA GUI for editing "auxiliary parameters." Items "grayed out" are not applicable.

self and mutual inductances of short solenoids. Assuming "mirror" currents in the armature,

$$L_{gen} = \sum_{i=1}^{v} L_i + \sum_{j=1}^{v}\sum_{i=1}^{v}(L_{mij} - L_{nij}) \,, \tag{1}$$

where $L_i$ is the self-inductance of the stator's $i$-th ring, $L_{mij}$ is the mutual inductance between the stator's $i$-th ring and stator's $j$-th ring, and $L_{nij}$ is the mutual inductance between the armature's $i$-th ring and the stator's $j$-th ring.

$L_{loss}$ corresponds to the field contained in a cylindrical shell of radial thickness $\Delta r_{flux}$ at the inner wall of the stator; it is calculated from

$$L_{loss} = \frac{2\pi\,\mu_0\, r_{stator}\,\Delta r_{flux}}{\Delta z}\sum_{i=i}^{n} N_i^2 \,, \tag{2}$$

where $\Delta z$ is the (uniform) axial length of the rings, and $N_i$ is the number of turns in the $i$-th ring. Only "live" rings are included in the sum above, and $L_{loss}(t)$ decreases with time. Thus, energy in the flux-loss layer is taken out of the circuit at a rate of $0.5\, I^2\, dL_{loss}/dt$.

Stator resistances are calculated using one-dimensional (radial) magnetic field diffusion equations. The stator winding shell is automatically gridded into 20-80 cylindrical sections with appropriate boundary constraints on the magnetic field at the shell's surfaces. The diffusion equations, along with ohmic heating, help determine the gross effective resistances of the stator.

Data plots available from FCGSCA include currents in the armature, stator, transformer windings, fuze(s) and load; electromagnetic energy stored in system inductances; ohmic losses throughout the FCG system; power; time-derivatives of all data; and miscellaneous other performance criteria.

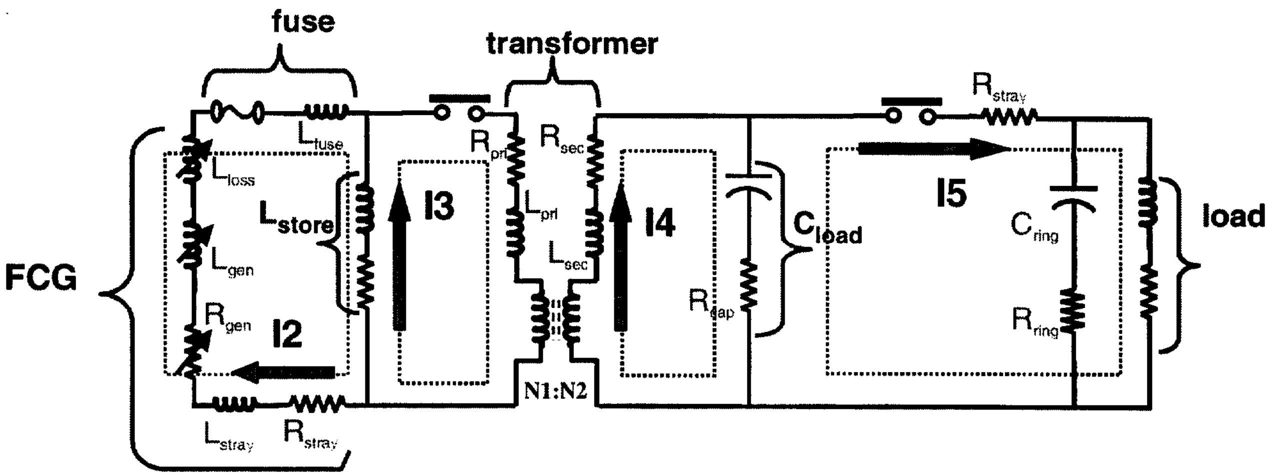


Figure 5. FCGSCA's basic electrical circuit topology for the helical generator configuration. "I1" is reserved for the radial configuration.

## IV. RANCHITO PARAMETERS

The Ranchito generator has been under development at LANL for several years; Ranchito provides a significant new capability for delivering megajoule pulses in numerous applications. The design requirements of this generator included a necessary energy high gain.

Some characteristics of the generator and test load are provided in Figures 1 through 4. The only other parameters not available from the FCGSCA GUI figures are the specifics of the stator's winding pattern, shown in Table I. (FCGSCA accepts such data via the GUI window of Fig. 4.) The Ranchito generator was connected to a 330nH, 2mΩ load.

**TABLE I: Ranchito Stator Winding Data**

| seg. | length | pitch | # wires | wire diameter |
|---|---|---|---|---|
| 1 | 29.2 cm | 1.04 cm | 2 | 0.411 cm |
| 2 | 29.2 | 2.09 | 4 | 0.411 |
| 3 | 25.4 | 4.23 | 8 | 0.411 |
| 4 | 19.1 | 7.64 | 14 | 0.411 |
| 5 | 19.3 | 12.87 | 24 | 0.411 |

## V. EXPERIMENTAL RESULTS

Although FCG test data usually includes load current, its time-derivative, and total load voltage, we will focus on the load current itself, due to spatial constraints for this publication. Figures 1 through 4, and Table I contain all the pertinent FCGSCA input data assumed for the Ranchito simulation. Figure 6 contains an overlay of FCGSCA's theoretical prediction and the actual Ranchito shot data; for the parameters chosen, FCGSCA accurately modeled the Ranchito shot to within the error margins of the Ranchito input data.

## VI. MODEL SENSITIVITIES

Certainly, the performance of an FCG depends upon the load inductance and the load resistance. The most significant other sensitivity in our model is the "flux-loss" term—the only heuristic "tweaking" knob in FCGSCA. We will conclude by briefly discussing the sensitivity of results to these three variables of interest.

The simulation data shown in Figures 7, 8, & 9 quantifies the sensitivity of Ranchito's load current to changes in these parameters individually, while Figure 10 shows a two-parameter study of peak load current versus load resistance and load inductance. We have found such plots useful and stimulating for investigating general design and load matching questions.

We expected and confirmed that reasonable values of the flux-loss width ($\Delta r_{flux}$) would be less than but perhaps comparable with the 0.411-cm diameters of Ranchito's stator wire. In general, the spreads in expected peak load current were about ±200kA for the listed (Figures 7,8, and 9) uncertainties in assumed parameters.

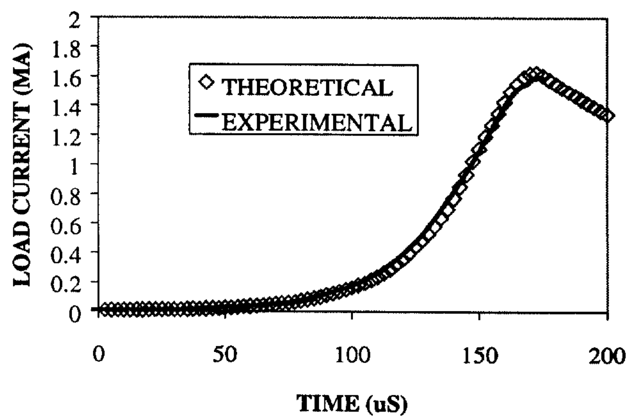

Figure 6. Experimental (bold, blue line—ending at 170μS) and theoretical (red diamonds) Ranchito current into a 330nH, 2mΩ load.

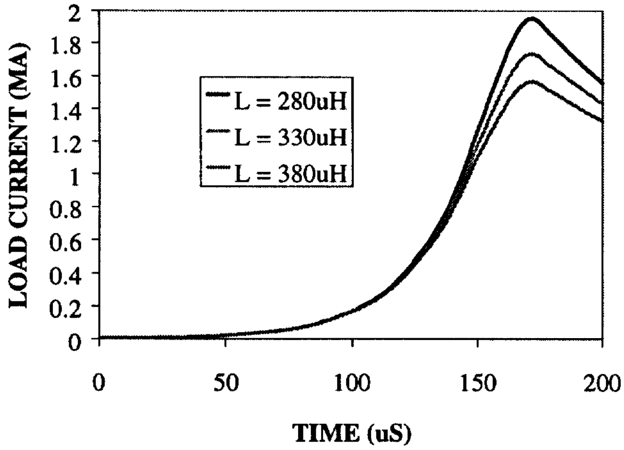


Figure 7. FCGSCA load inductance sensitivity study for the Ranchito generator. The upper plot corresponds to L = 280uH.

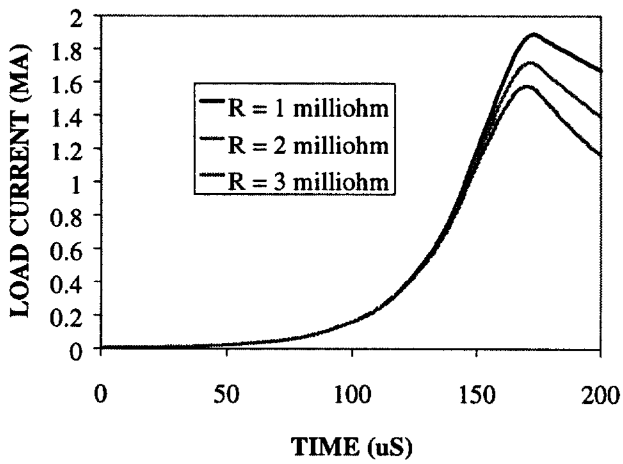


Figure 8. FCGSCA load resistance sensitivity study for the Ranchito generator. The upper plot corresponds to R = 1 milliohm.

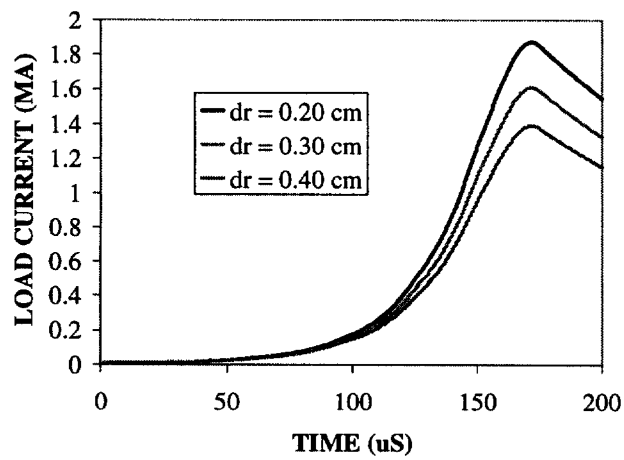


Figure 9. FCGSCA "flux-loss" sensitivity study for the Ranchito generator. The upper plot corresponds to dr = 0.20cm.

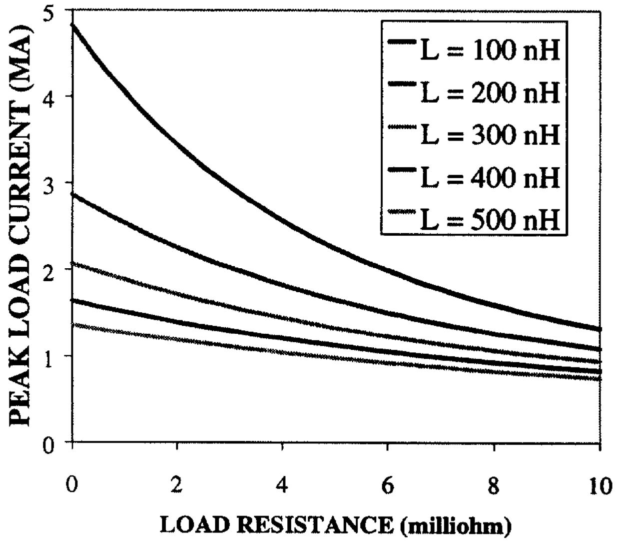


Figure 10. Two-parameter variation study; peak load current versus variations in the load inductance and load resistance. In FCGSCA, many other two-parameter variation studies are possible.

## VII. CONCLUSIONS

The FCGSCA code continues to improve, and its simulation results to date are encouraging, given that the incorporated models are based on one- or two-dimensional approximations that ignore many higher-order effects. The practical nature and utility of FCGSCA has perpetuated our interest in further development of the underlying simulation models. As improvement of the simulation improves, the GUI will likely be improved also. As a final word, we will continue to be interested in securing opportunities to benchmark FCGSCA with other generator experiments.

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[2] Prior reporting in the *Proceedings of the 7$^{th}$ (1996) Int'l Conf. on Megagauss Magnetic Field Generation and Related Topics*—in print.

[3] F.W. Grover, *Inductance Calculations: Working Formulae and Tables*, Dover Publications Inc., (1962).